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Seismic stratigraphy of Lago Fagnano sediments (Tierra del Fuego, Argentina) - A potential archive of paleoclimatic change and tectonic activity since the Late Glacial

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ABSTRACT

Located at 54° S in the heart of the Island of Tierra del Fuego, Lago Fagnano occupies the deepest of a chain of *en-echelon* tectonic depressions along the Magallanes-Fagnano Transform system (MFT). A recent geophysical campaign combining 3.5 kHz (pinger) single-channel with 1 in^3 airgun multi-channel systems surveyed more than 100 m of glacio-lacustrine sediments filling two main sub-basins. These data provide a unique opportunity to visualize the most recent lacustrine sequence with high-resolution while simultaneously imaging the oldest infill. A preliminary seismic stratigraphic analysis of the high-resolution 3.5 kHz pinger data allowed the identification of three major seismostratigraphic units (A, the oldest and C, the youngest). While unit A is interpreted as glacially derived sediments, the overlying unit B is interpreted as fining upward sequences of proglacial turbidites reflecting sediment pulses released by the retreating Fagnano glacier during the last deglaciation. A major environmental change occurred during deposition of unit C when pelagic style of sedimentation is intercalated by sequences of downslope mass flow events probably triggered by relatively strong tectonic pulses along the MFT system. Gravity cores show a regular alternation of light and dark laminae occasionally interrupted by homogenous sedimentary units interpreted as turbidites. Ultra-high resolution X-ray fluorescence micro-profiles show fluctuations in major trace elements at mm scale that may indicate seasonal variations in the sedimentary influx. These core data provide a unique record of decadal changes in regional climate that can be compared with other marine and continental archives to improve our understanding of the forcing mechanisms behind climate change.

KEYWORDS Paleoseismology. Lacustrine sedimentation. Turbidites. Paleoclimate

INTRODUCTION

Lacustrine sediments provide one of the best continental archives of environmental change (Gierlowski-Kordesch and Kelts, 2000). In addition, many lakes are located in tectonically sensitive regions; therefore, their sedimentary record may also archives regional tectonic events (Chapron et al., 1999). Thus, lacustrine basins can play a key role in reconstructing the paleoclimatic record while disentangling superimposed paleotectonic imprints.

Acoustic methods, such as high-resolution seismic reflection profiling, are crucial tools for studying lacustrine basins, their structure and their sedimentation regime. High-resolution seismic sequence analysis is becoming a routine approach to lake studies. Scholz and Rosendahl (1988) first applied principles of sequence stratigraphy to large African rift-valley lake systems, and more recently seismic-stratigraphic studies have been successfully used to reconstruct past environmental changes in a variety of lacustrine settings (Moore et al., 1994; Seltzer et al., 1998; Abbott et al., 2000; Ariztegui et al., 2001; Gilli et al., 2001; Schnellmann et al., 2005; Ariztegui et al., in press). In this paper, we present seismic reflection data from the Argentinean section of Tierra del Fuego's Lago Fagnano (Argentina/Chile), showing the potential of this basin, the southernmost large body of unfrozen fresh water in the world, to reconstruct past environmental changes. This article further explores Lago Fagnano sediments as a potential archive of earthquake-triggered mass-wasting events, thereby investigating the paleo-earthquake history of the southernmost tip of South America. Both 3.5 kHz and small airgun seismic-reflection data and the corresponding seismic stratigraphic analysis were calibrated with sedimentary cores covering the uppermost part (~1-8 m) of the seismic profiles. Our preliminary geophysical and sedimentological results support the potential of this lacustrine sequence to reconstruct both the paleo-seismicity history of southernmost South America as well as its paleoclimatic evolution since the Last Glacial. Continuous records of former climates from such far Southern Hemisphere areas are scarce and are essential both for linking continental Patagonia with Antarctic climate records and for comparing the paleoclimate evolution of the Northern and Southern hemispheres.

MORPHOLOGICAL AND GEOLOGICAL SETTINGS OF LAGO FAGNANO

The island of Tierra del Fuego is the southernmost large landmass in the world, other than Antarctica. This island is bounded by the southern Atlantic Ocean to the east and the southern Pacific Ocean to the west. At 54°S, Lago Fagnano (or Lago Kami in the native Yamana language) lies along the southern half of the island. With a total area of more than 560 km^2, this oligotrophic, latitudinally elongated lake (Mariazzi et al., 1987) of ~105 km length with a maximal width of ~10 km is the southernmost and largest ice-free water body in the world (Fig. 1). Located along a major plate boundary and under the Andean glaciations, the lake has a combined tectonic and glacial origin. Sediment accumulation probably covers the entire Holocene and may date back even to the Last Glacial Maximum (LGM) (Bujalesky et al., 1997).

Currently, the climate of this region is alpine, with a strong winter sub polar-Antarctic influence. Lago Fagnano lies at the southernmost limit of the southwesterly wind influence that brings moisture and humidity to the region during austral summer. This situation, however, may have changed during the Last Glacial and Late Glacial periods, as shown by other southern Patagonian climatic archives (e.g., Gilli et al., 2001; Douglass et al., 2005).

The lake comprises two sub-basins: a smaller, deeper basin in the east reaching a maximum depth of 210 m, and an elongated, shallower basin in the west exhibiting ~110 m maximum water depth (Fig. 1). The southern shores are bordered by the foothills of Sierras de Alvear (eastern part of Cordillera Darwin), while the lower mountain belt of the Sierras de Beauvoir borders the northern margin of the lake. The Claro, Milna, Valdez and Turbio rivers all drain into this lake, whereas the Azopardo River at the western extreme of the lake is the only outlet towards the Pacific Ocean, through the Almirantazgo Fjord (Admiralty Sound) and the Straits of Magellan.

The lake occupies the deepest continental pull-apart basin in a series of graben-shaped, asymmetric tectonic sinks organized in an *en-echelon* arrangement along the Magellan-Fagnano Transform (MFT) (Lodolo et al., 2003, 2007; Tassone et al., 2005; Menichetti et al., this issue). The onset of horizontal left-lateral movement along the MFT is not well dated, but is presumed to have started during the Oligocene (Klepeis, 1994; Lodolo et al., 2003). Recent fault scarps and displacement of glacio-lacustrine sediments along the transform lineation in and co-linear with the eastern part of the lake indicate ongoing tectonic activity (Dalziel, 1989; Menichetti et al., 2001). Moreover, fluvial drainages in the same region are clearly influenced by the presence of latitudinal structures related to the strike-slip fault system (Menichetti et al., 2001).

The bedrock substratum along the southern flanks of the lake includes low-grade metamorphic black shale and whitish-gray tuff sequences, corresponding to a Late Jurassic marine volcano-sedimentary complex (Le Maire Formation; Borrello, 1969). The northern and eastern margins of the lake are composed of folded Lower Cretaceous to Tertiary marine greywacke (Yahgan and Beauvoir Formations; Caminos et al., 1981; Olivero and Martinioni, 2001). An Upper Cretaceous monzodioritic body (Cerro Hewhoepen batholith) intrudes the formations at the southeast extreme of the lake (Acevedo et al., 2000).

The instrumentally recorded seismicity along the transform boundary is low (M_w<3.5) and shallow (Vuan et al., 1999). Strong, historically documented seismic events, however, have also occurred. The last earthquake that affected the Island of Tierra del Fuego occurred in 1949 (M_w=7.8); its epicenter was located along the MFT in the Atlantic several tens of kilometers off the island's coast. This earthquake caused the subsidence of large areas close to the lakeshores, forming a series of lagoons still connected to the main lake. Moreover, this seismic event triggered several landslides along the banks of Lago Fagnano (Menichetti et al., 2001) and also in the westernmost arm of the Straits of Magellan, where tsunami waves were observed (Jaschek et al., 1982). Hence, the sedimentary infilling of the lake offers an exceptional possibility for reconstructing both the paleoclimatic history of the region as well as the paleoseismic history of the MFT. Here, we discuss for the first time data bearing on climate and tectonic controls on Lago Fagnano sedimentation, using a geophysical approach combining two different reflection seismic systems, along with preliminary sediment characterization as deduced by grab samples, gravity and piston cores (Fig. 1).

METHODOLOGY

Seismic survey

In March 2005, we acquired more than 800 km of geophysical data during a cruise of the *R/V Neecho* in the Argentinean side of Lago Fagnano, collecting simultaneously single-channel, high-resolution 3.5 kHz (pinger) and 1 in^3 airgun multi-channel seismic data. Seismic profiles were digitally recorded in SEG-Y format, using a non-differential global positioning system (GPS) with an average accuracy of ±5 m. While the pinger survey provides seismic stratigraphic information about shallow subsurface sediments (to depths of several tens of

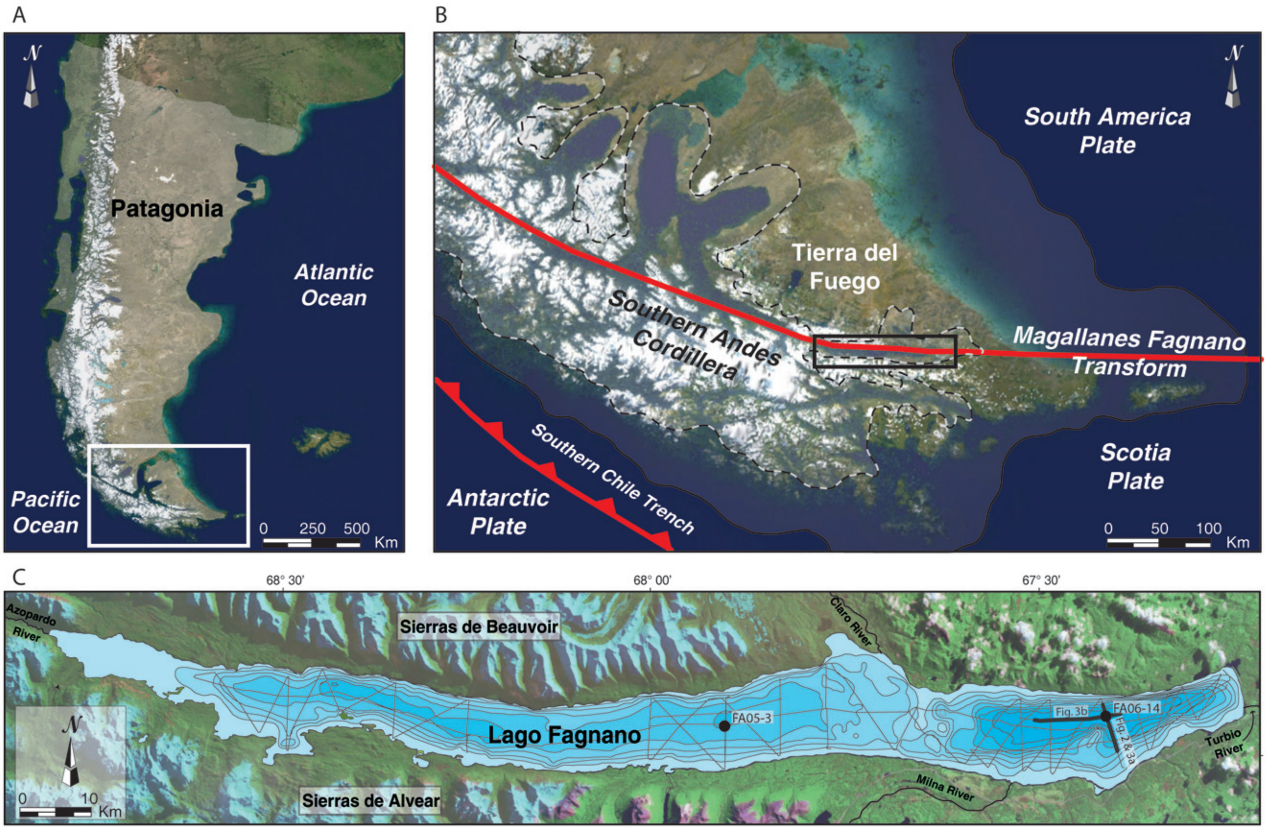

FIGURE 1 **A) Location map of Patagonia. B) Satellite image of Tierra del Fuego. Dashed line mark the maximum extension of ice during the LGM while dark line stand for the coastline at LGM times (Rabassa et al., 2000). C) Bathymetric map of Lago Fagnano with a 20 m contour interval (modified from Lodolo et al., 2002) showing our entire seismic grid. Thicker lines and solid dots indicate the location of the seismic profiles and sedimentary cores presented in this article, respectively.**

meters), the airgun survey images the deeper sedimentary deposits and bedrock morphology of the basin. Pinger data were processed by band pass filtering (2-6 kHz) and gaining with Automatic Gain Control (AGC; window length 100 ms). Airgun data were also band pass filtered (200-1,000 Hz) and gained (AGC 200 ms). Constant shallow noise was digitally removed and a water bottom mute was applied. The seismic data were interpreted using the Kingdom Suite™ software developed by Seismic Micro-Technology Inc. For calculation of velocity analyses and bathymetry, an average water column velocity of 1,500 m/s was assumed. Water depths around the basin were confirmed during surface sediment sampling using a sediment grab sampler on a metered cable.

Coring

Coring sites were targeted at selected locations based on the preliminary interpretation of the seismic data. Short gravity cores of ~1-2 m in length and up to 8.5 m long Kullenberg-type piston cores were retrieved in March 2005 and March 2006, respectively. This paper focus on the preliminary data from two selected cores collected from the center and eastern parts of the lake (Fig. 1). The cores were cut into 1 to 1.5 m pieces for transport and further storage in a dark cold room at 4ºC. They were scanned prior to opening at the ETH-Zurich with a GEOTEK™ multi-sensor core logger (MSCL) to obtain the petrophysical properties (P-wave velocity, gamma-ray attenuation bulk density and magnetic susceptibility). Calibration of the MSCL instrument was done at the beginning of each analyzed core using an aluminum and water standard.

The sedimentary cores were photographed immediately after splitting and described in detail. Preliminary sampling included smear slide analysis to characterize sediment type and major components, as well as routine geochemistry. Elemental determination and mapping in selected samples at ca. 50 μm resolution were carried out at the University of Geneva with a non-destructive Röntgenanalytik Eagle II micro X-Ray fluorescence system. Acquisition parameters of the Rh tube were set at 40 kV and 800 mA and the raw intensity of individual elements were normalized to Ca to highlight their relative variations.

RESULTS

Seismic stratigraphy

Acoustic penetration by the 1 in^3 airgun/multi-channel seismic system into the subsurface of Lago Fagnano was deep enough to image bedrock, revealing a glacio-lacustrine sedimentary infill that reaches >100 m thickness in the eastern basin (Fig. 2). Preliminary analysis of these data indicates a complex bedrock morphology that is overlain by interpreted moraine and subglacial deposits that in turn are buried by a lacustrine succession. Ongoing processing and interpretation of all of these data should allow determination and mapping of their variation in geometry and thickness throughout the basin. While the 1 in^3 airgun system better visualizes the deeper parts of the subsurface, the pinger seismic data provides critical information at higher resolution for the shallower sediments within both deep basins. A preliminary seismic stratigraphic analysis of the high-resolution 3.5 kHz pinger data on all profiles in the easternmost basin has allowed the identification of three major seismostratigraphic units (A-C) with different seismic facies. Unit A is the oldest of the imaged seismic section, whereas unit C corresponds to the youngest deposits (Fig. 3). Only its top is imaged by the 3.5 kHz data, whereas the base is mostly beyond seismic penetration. Reflections within seismic unit A can be detected in some areas up to 25 m below the unit's top, before seismic energy fades, defining thick unstructured and irregular subunits. The top of this unit is formed by an up to ~10 m-thick transparent subunit that focuses in preexisting basin depressions (Fig. 3B).

Seismostratigraphic unit B overlies unit A, comprising a series of more than ten transparent subunits separated by almost equally spaced continuous medium-to-high amplitude reflections (Fig. 3). The spacing of these higher amplitude reflections gets gradually thinner towards the top of the unit. The uppermost succession in unit B consists of a sequence of very high-amplitude and parallel reflections. The unit averages ~5 m in thickness but thickens towards the deeper basinal areas in contrast to the youngest unit C that has a locally more draping geometry, at least in the northern part of the eastern basin. Unit C's seismic facies is characterized by intercalations of thinly spaced, high-amplitude internal reflections with low-amplitude to transparent intervals that get much thicker southward. These transparent subunits are usually lens-shaped and have partly erosive lower boundaries and hummocky upper boundaries, showing sharp lateral transitions into the more highly reflective seismic facies. Overall, the entire sequence thickness increases toward the south, reaching >25 m, whereas it is only 8 m thick in the northern part of the basin.

Core sedimentology

Gravity core FA05-3 (Fig. 4) recovered the uppermost part of seismostratigraphic sequence C in the central part of the lake (see Fig. 1 for location). This core yielded 160 cm of uniformly laminated, brown silty clay intercalated with thin, dark green to black, clay-enriched laminae with

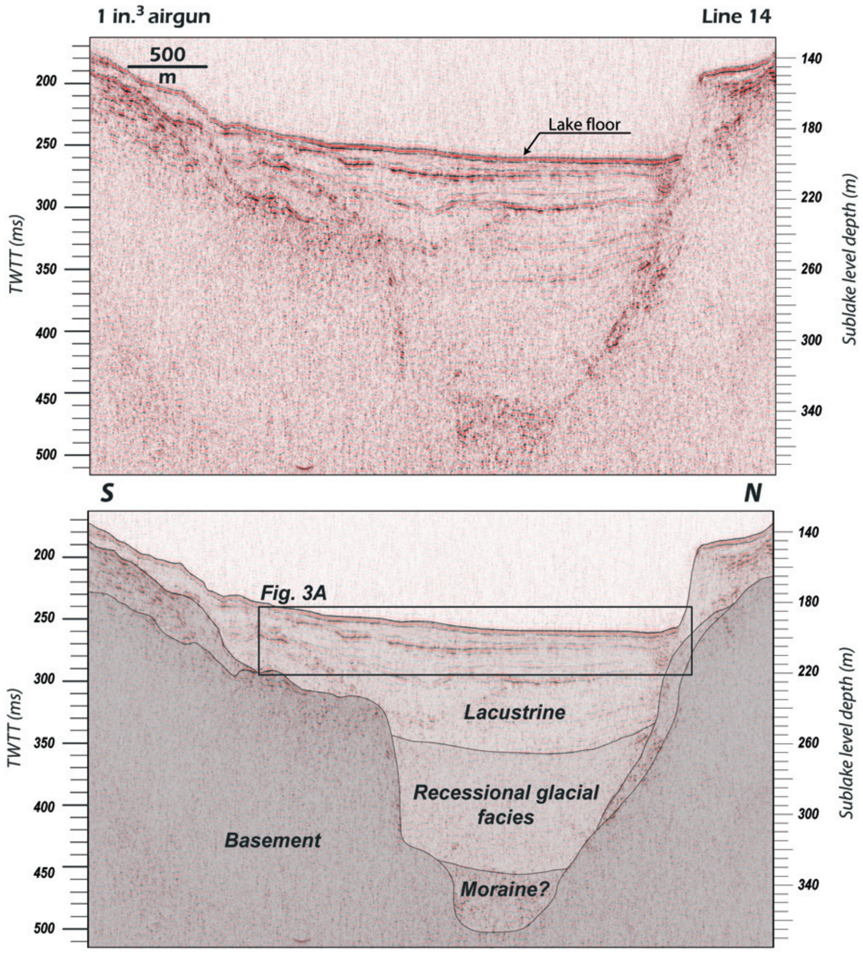

FIGURE 2 **Uninterpreted (above) and interpreted (below) processed, N-S, multi-channel, 1 in^3 airgun seismic profile (see Figure 1 for location). Sediment depth is given in both milliseconds of two-way traveltime (TWTT) and consequently converted to sub-lake level depth (m) based on a P-wave velocity of 1,500 m/s for water and sediment.**

dominant diatoms and amorphous organic matter contents. Ultra-high resolution elemental analysis of bulk sediments reveals that the dark green laminae are enriched in Fe and Mn, whereas the intercalated brown clay, medium-size laminae are primarily dominated by Ca, Ti and K (Fig 4). This lithology is interrupted at the bottom of the core by a thick, light brown, homogenous layer composed of silt and clay with relatively high susceptibility values.

Piston core FA06-14 (Fig. 5) from the eastern part of the lake is ~7.5 m in length and recovered part of the sedimentary succession from unit C. The internal seismic architecture of this unit coincides well with sudden variations in the petrophysical properties measured in this core, allowing a precise core-to-seismic correlation. Whereas bulk density in the core shows a general downcore increasing pattern, the small-scale density changes, along with variation in magnetic susceptibility and P-wave velocity throughout the core, are closely related to internal lithological changes and are linked to high-amplitude reflections in the seismic profile. Very high magnetic susceptibility values such as those in the lower part of core FA06-14 may also correspond to interpreted tephra layers, which will be confirmed with further analysis.

DISCUSSION

Seismic stratigraphy

A preliminary interpretation of the seismic stratigraphy of the eastern and deepest basin in Lago Fagnano suggests that seismostratigraphic unit A corresponds to glacially-derived sediments, as known from other lacustrine records (e.g., Finckh et al., 1984). This unit may represent subglacial to proglacial sedimentation probably deposited at the end of the Late Glacial period during the retreat of the eastern lobe of the Fagnano glacier (Coronato et al., 2005). This unit's irregular seismic character, with thick, transparent subunits separated by high-amplitude reflections that infill basin irregularities (Fig. 3B) suggests that the glacier was located very close to the basin and was experiencing both temporary advances and retreats, attended by proglacial melt-water plumes which triggered slope instabilities that ponded in topographic lows. The occurrence of higher-amplitude, discontinuous reflections towards the top of the uppermost mass flow in this unit suggests lower energy depositional conditions, and more internal sediment stratification within the finer grained fraction of the mobilized sediments that were deposited towards the end of the mass-flow event. We conclude that unit A comprises a classic proglacial environment in front of an (overall) retreating glacier.

The equal spacing of thin transparent units, separated by high-amplitude reflections characteristic of seismostratigraphic unit B, may represent fining upward sequences of proglacial turbidites or of small slides reflecting sediment pulses released by the retreating Fagnano glacier to the basin during deglaciation. The high-amplitudes are likely caused by the coarse-grained (and thus high-impedance) bases of debris flows; intercalated with these flows are clays and silts that settled gradually from suspension (e.g., Badley, 1985; Eyles et al., 2003). The gradual upward variation within unit B into more closely spaced, high-amplitude reflections suggests a gradual change in sedimentation towards thinner and more frequent flows, probably in a more distal proglacial environment. A major sedimentary change occurs associated with the transition into seismostratigraphic unit C. To the north, a draping geometry indicates a pelagic style of sedimentation in a basin that is no longer in direct contact with the glacier, as is known from the Holocene succession in former proglacial lakes (Girardclos et al., 2005). To the south, thickening of unit C caused by the lens-shaped, seismically-transparent bodies must represent downslope mass flow events that were triggered on the laterally along the southern slopes of Lago Fagnano, as has been previously recognized in many fjord environments (Piper et al., 1999; Canals et al., 2004; St-Onge et al., 2004; Gervais et al., 2006, among others), as well as in alpine lake systems (Chapron et al., 1999; Shiki et al., 2000; Schnellmann et al., 2002, 2005; Strasser et al., 2006). This stacked series of mass-flow events pinches out northward and shows a transition into what we suggest are megaturbidites (e.g., Schnellmann et al., 2005). While the mass-flow deposits are shown in the seismic profiles as wedges of chaotic to transparent seismic facies with smooth to slightly hummocky top surfaces, the relatively thin, distal parts of these deposits generally overlie undisturbed, acoustically layered sediments (Fig. 3). Close to the base of the southern slope, the mass-flow deposits are thicker and the underlying sediments are also seismically chaotic (Fig. 3A and B). Such an occurrence of large mass-flow deposits, as in youngest unit C, has been previously described in several Swiss alpine lakes, where it has been interpreted as documenting the onset of

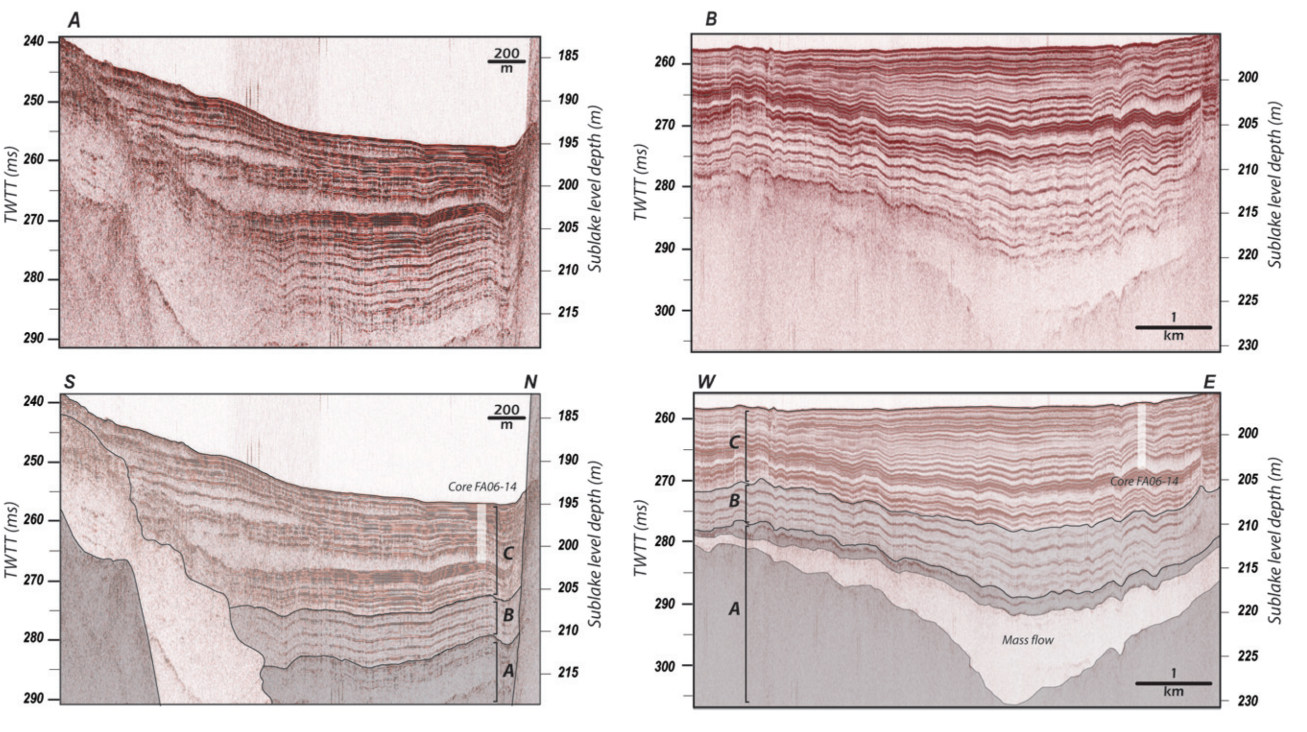

FIGURE 3 **Uninterpreted (above) and interpreted (below) processed, 3.5 kHz, N-S and E-W, seismic sections across the eastern part of the basin (see Figure 1 for location). Letters indicate seismic units discussed in the text. Core locations are labeled. Sediment depth is given in milliseconds of two-way traveltime (TWTT) and consequently converted to sub-lake level depth (m) based on a P-wave velocity of 1,500 m/s for water and sediment. Notice the different horizontal scales in both profiles.**

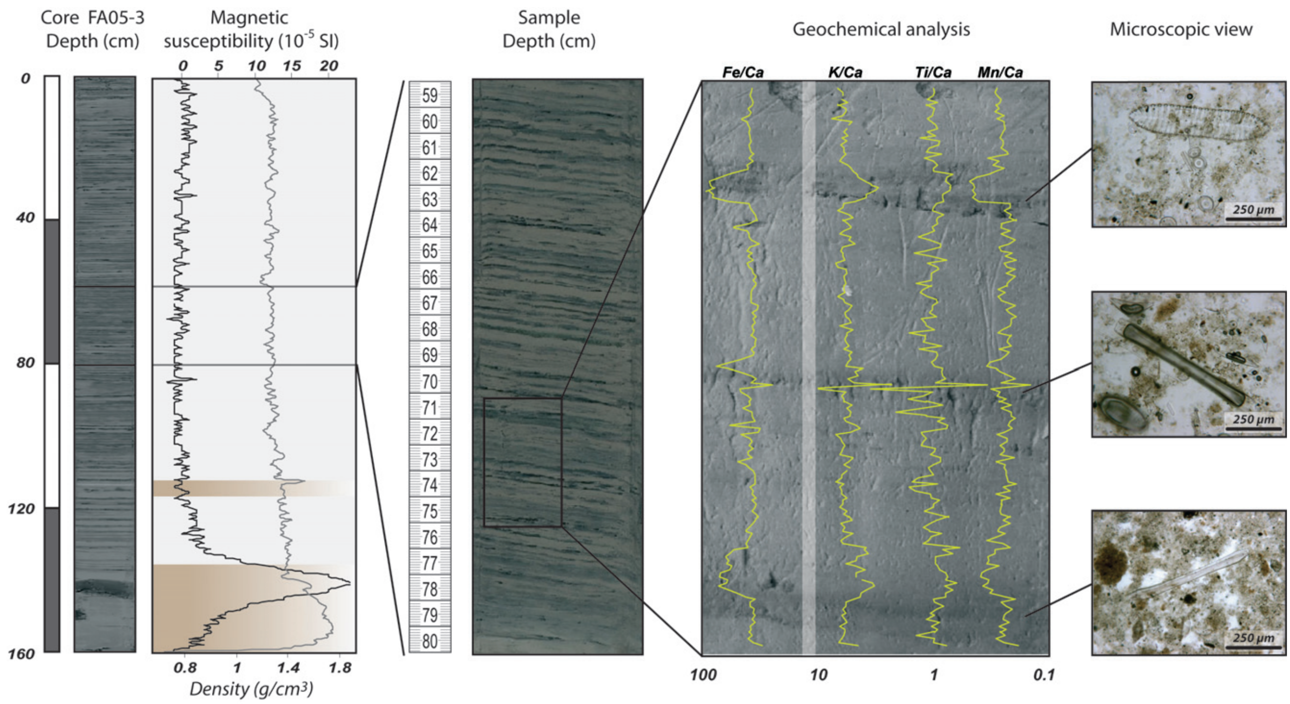

FIGURE 4 | **Gravity core FA05-3 (depth in m) picture, as well as magnetic susceptibility (solid line) and density (dashed line) profiles. Gray shading indicates interpreted turbidite layers. The excellent mm-scale lamination is clearly displayed in a detailed photograph (depth in cm). Ultra high resolution X-ray fluorescence analyses on a selected sample reveals high Mn/Ca and Fe/Ca ratios in the dark laminae, while high Ti/Ca and K/Ca characterize the thicker, lighter laminae. Gray shading indicates sampling location. A microscopic inspection of the dark laminae shows high diatom concentrations and occurrences of amorphous organic matter (see text for more explanation).**

Holocene pelagic-type slope and basin sedimentation that provides material to become destabilized and redeposited (Schnellmann et al., 2002, Strasser et al., 2006). In Lago Fagnano, at least ten mass-movement events are recognized in the eastern part of the lake; perhaps these individual events are triggered by relatively strong tectonic pulses along the MFT. Further basin-wide analysis may confirm whether or not earthquake shaking may have triggered these flow events. Almost no such slides were recognized with an origin from the northern slope, because in contrast to the more gentle southern area, the slope angles are here too steep for pelagic-type sediment accumulation.

Sedimentology

The sedimentary infill of Lago Fagnano likely represents a continuous record since the Late Glacial (Bujalesky et al., 1997; Coronato et al., 2005). The seismic facies with parallel high-amplitude reflections in the basinal part of seismostratigraphic unit C and the recovered lithologies indicate that the top of this unit is a drape of unconsolidated, very fine-grained clay and silt. This lithology is comparable to that of other lacustrine settings, where similar seismic facies are usually interpreted as a late lake stage mud drape resulting from a uniform suspension below wave base (e.g., Van Rensbergen et al., 1999). The laminated pattern of these deposits suggests sedimentation at an annual or seasonal level in a well-stratified lake, although accurate dating will confirm if they are indeed varves. Lamination is preserved by an anoxic or dysoxic sediment/water interface environment, thereby preventing bioturbation. Fe and Mn enrichment in the dark laminae may be associated with dominant redox conditions, with the precipitation of iron-hydroxides. The large diatom content in the dark-green laminae (Fig. 4) indicates increasing productivity during the wet rainy summer season, when the moisture mainly arrives from the Pacific Ocean, carried by the Southern Hemisphere Westerlies. However, this climatic pattern may have varied in the past during the Late Glacial period, when the influences of the southern Pacific Gyre and Polar outbreaks may have been stronger than today. Latitudinal shifts in the Southern Hemisphere Westerlies have been proposed to occur since the middle Holocene (Markgraf, 1993); however, the position of these zonal winds through time is still controversial (Lamy et al., 1999; Markgraf et al., 2000; Jenny et al., 2002) and more research is needed to clarify this issue. Our paleoclimatological reconstruction from Lago Fagnano should furnish more information related to the positioning of these winds, and may also provide additional data to constrain the forcing mecha-

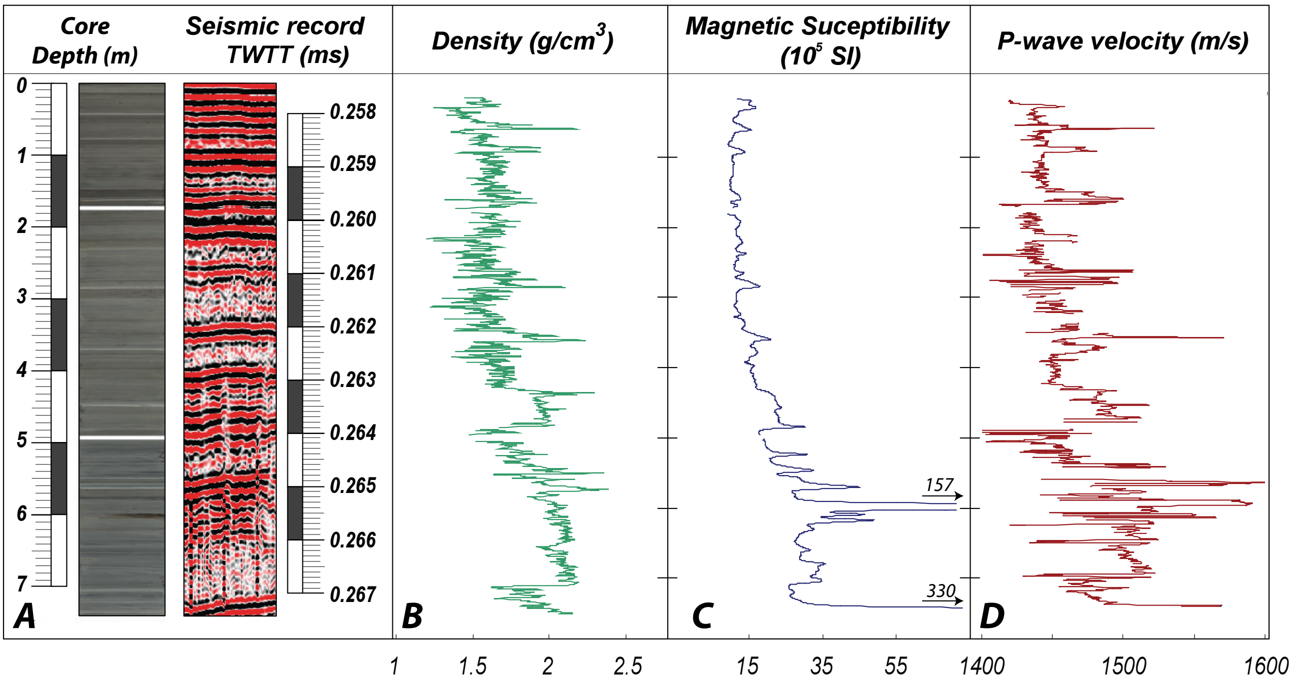

FIGURE 5 **Seismic profile and petrophysical data (P-wave velocity, bulk density and magnetic susceptibility) for piston core FA06-14. A) Original seismic record at core site (depth in m and two-way traveltime in ms). B) gamma-ray attenuation bulk density (g/cm3). C) magnetic susceptibility (10-5 SI). D) P-wave velocity (m/s). Refer to text or discussion.**

nism behind climate change in the southernmost extreme of South America since the Late Glacial.

The chaotic, massive unit 140 cm below the sediment surface of core FA05-3, accompanied by stable but higher values bulk density and magnetic susceptibility (Fig. 4), indicate a turbidite deposit from slope failure, probably triggered by a seismic event (e.g., Strasser et al, 2006). Assuming that this conspicuous lithological feature is associated with the 1949 Mw=7.8 event, the sedimentation rate for the upper part of the sedimentary record will be of ~2.45 cm/y, yet a more refined chronology is needed to support this hypothesis. Laminae counting yields 170 light/dark laminae couplets, which for a 135 cm sediment thickness would indicate a sedimentary rate of 0.8 cm/year suggesting that this turbidite is too old and may not correspond to the 1949 (Mw=7.8) event. The latter would imply the formation of more than a lamina per year. The ongoing development of an independent chronology will enable to discern between these two possibilities.

CONCLUSIONS

The subsurface of Lago Fagnano, Tierra del Fuego, has been imaged for the first time with 800 km of seismic reflection profiles. The upper sedimentary succession has also been retrieved with a series of sediment cores. High-resolution 3.5 kHz seismic profiles provide excellent images of the near-surface sediments. These data were combined with multi-channel, small airgun data that better visualize deeper sedimentary structures. The resulting seismostratigraphic architecture of the easternmost lacustrine basin allows us to reconstruct in a preliminary way the successive depositional processes that characterize the last deglaciation in Lago Fagnano. The calibration of the most recent section of the seismic profiles with core data confirms that distinctive changes in seismic character correspond to major lithological changes. The latter validates the use of a seismic stratigraphic approach to reconstruct basin-wide sedimentological processes.

The seismic stratigraphy and core-to-seismic correlation of Lago Fagnano sediments show more than ten major mass-flow units that appear to record mass-wasting events, perhaps triggered by tectonic movements along the MFT system. Additionally, the recovered laminated sequence, comprising a regular succession of dark lamina enriched in iron hydroxides and diatoms, and intercalated light brown clay-rich lamina, suggests seasonal changes in the sedimentation that are climatically controlled. However, the mechanism behind their formation is still unknown. We speculate that it may be controlled by seasonal variation of the Southern Hemisphere westerly winds that bring humidity to this region from the Pacific Ocean. Further analysis should provide more information to reconstruct both the climate and the tectonic history of this region since Late Glacial times. Lago Fagnano further illustrates the use of a combined geophysical and sedimentological approach to separate the complex influence of climate and active tectonics on lacustrine sedimentation.

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